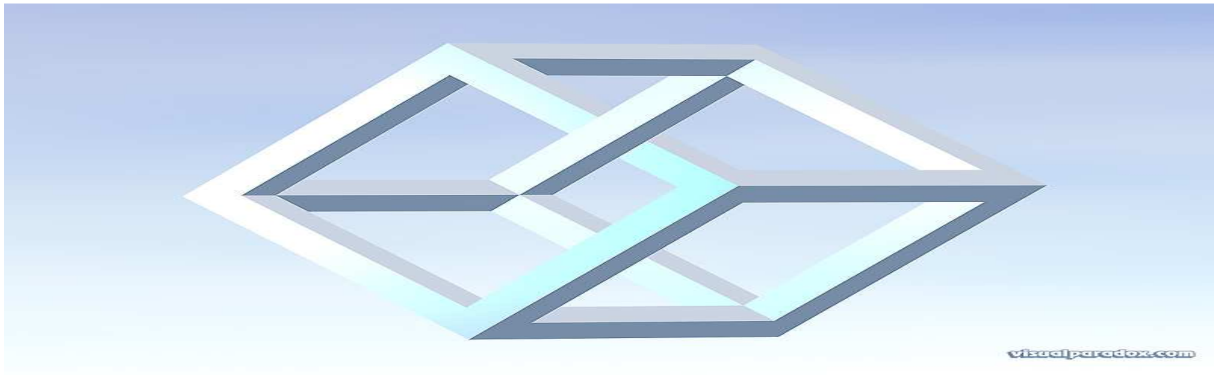
Beyond the Four Known Forces of Nature

Bogdan Dobrescu (*Fermilab*)



The four forces

1. Electromagnetic interactions

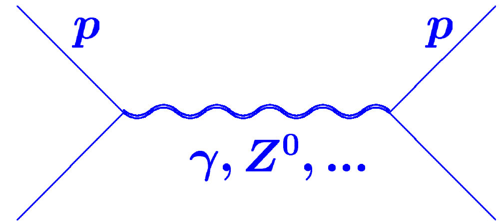
2. Weak interactions

3. Strong interactions

4. Gravitational interactions

The four forces

One-boson-exchange:



1. **Electromagnetic interactions**

   Coulomb force: $\sim \frac{1}{r^2}$ *(massless spin-1 particle exchange: photon)*

2. **Weak interactions (short range)**

   "Z^0-exchange force": $\sim \frac{1}{r^2} \exp\left[-2r/(10^{-16}\mathrm{cm})\right]$

3. **Strong interactions (short range)**

   Gluon-exchange force:
   $$\frac{1}{r^2\left[1 - b\ln\left(\frac{r}{10^{-14}\ \mathrm{cm}}\right)\right]}$$

   (approximation breaks down at $r \gtrsim 10^{-14}$ cm $\rightarrow$ confinement)

4. **Gravitational interactions**

   Newton's law: $\sim \frac{1}{r^2}$ *(spin-2 "graviton" exchange?)*

Gauge symmetry

The laws of physics have a $U(1)$ gauge symmetry if the Lagrangian is invariant under the gauge transformation:

$E(x^\mu) \to E'(x^\mu) = e^{-i\alpha(x^\mu)} E(x^\mu)$ (E is the electron field)

That requires a spin-1 field: the photon $A_\mu(x) \to A_\mu(x) - \partial_\mu \alpha(x^\mu)$

$$\mathcal{L}(x^\mu) = \overline{E}(x^\mu)\gamma^\mu \left[i\partial_\mu - eA_\mu(x^\mu) \right] E(x^\mu) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$F_{\mu\nu} = \frac{\partial A^\nu}{\partial x_\mu} - \frac{\partial A^\mu}{\partial x_\nu}$$

Quantum electrodynamics has been verified experimentally with an accuracy of 10^{-12}.

Photon mass term, $A_\mu A^\mu$, is not gauge invariant

$\Rightarrow$ $U(1)$ symmetry keeps the photon massless!

Electroweak symmetry

$SU(2)_W \times U(1)_Y$ **gauge symmetry: 4 gauge bosons** $\rightarrow\ \gamma,\ W^{\pm},\ Z^0$

MORE KINDS OF "LIGHT" ?!?

Not really, $W^{\pm}$ **and** Z^0 **are heavy (**$M_W \approx 80$ **GeV,** $M_Z \approx 92$ **GeV)**

Millions of them produced, especially at the
LEP (CERN) and Tevatron (Fermilab) colliders

If the laws of physics are gauge invariant,

where are the $W^{\pm}$ **and** Z^0 **masses coming from?**

Electroweak symmetry breaking

Lagrangian has an $SU(2)_W \times U(1)_Y$ gauge symmetry

Vacuum has only a $U(1)_{\rm em}$ gauge symmetry.

Electroweak symmetry is spontaneously broken

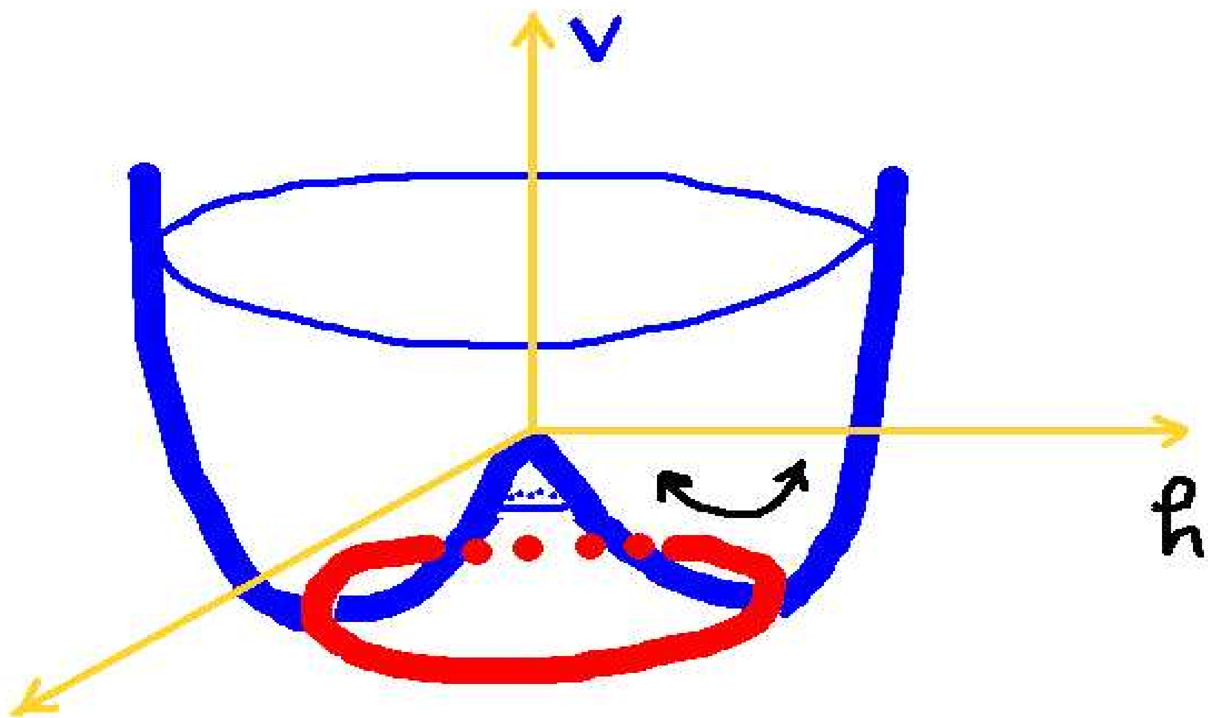
Similar to superconductivity!

In the Standard Model: the Higgs field has a

Vacuum Expectation Value ($v_h = 174$ GeV, "electroweak scale")

Higgs potential

e.g., spontaneous breakdown of a $U(1)$ *symmetry:*



The flat direction corresponds to massless modes that become the longitudinal components of the gauge bosons.

The Higgs boson is the mode transverse to the flat direction.

Elementary particles "observed" in experiments:

$$\left.\begin{array}{l}
\textbf{leptons} \left\{ \begin{array}{ccc} \begin{pmatrix} \nu_L^e \\ e_L \end{pmatrix} & \begin{pmatrix} \nu_L^\mu \\ \mu_L \end{pmatrix} & \begin{pmatrix} \nu_L^\tau \\ \tau_L \end{pmatrix} \\ e_R & \mu_R & \tau_R \end{array} \right. \\[2em]
\textbf{quarks} \left\{ \begin{array}{ccc} \begin{pmatrix} u_L \\ d_L \end{pmatrix} & \begin{pmatrix} c_L \\ s_L \end{pmatrix} & \begin{pmatrix} t_L \\ b_L \end{pmatrix} \\ u_R & c_R & t_R \\ d_R & s_R & b_R \end{array} \right.
\end{array}\right\rangle \textbf{(spin 1/2)}$$

$\overbrace{SU(3)}^{}$ $\times SU(2) \times U(1)$ **gauge bosons** **(spin 1)**

$\text{8 gluons} + W^\pm, Z, \gamma$

longitudinal $W^\pm$**,** Z **(spin 0)**

Standard Model of Particle Physics

$$\left.\begin{array}{ll}
\textbf{leptons} & \left\{\begin{array}{ccc}
\begin{pmatrix}\nu_L^e \\ e_L\end{pmatrix} & \begin{pmatrix}\nu_L^\mu \\ \mu_L\end{pmatrix} & \begin{pmatrix}\nu_L^\tau \\ \tau_L\end{pmatrix} \\
e_R & \mu_R & \tau_R
\end{array}\right. \\
 & \\
\textbf{quarks} & \left\{\begin{array}{ccc}
\begin{pmatrix}u_L \\ d_L\end{pmatrix} & \begin{pmatrix}c_L \\ s_L\end{pmatrix} & \begin{pmatrix}t_L \\ b_L\end{pmatrix} \\
u_R & c_R & t_R \\
d_R & s_R & b_R
\end{array}\right.
\end{array}\right\rangle \text{(spin 1/2)}$$

$\overbrace{SU(3)}^{\text{8 gluons}} \times SU(2) \times U(1)$ gauge bosons (spin 1)

$\text{8 gluons} + W^{\pm}, Z, \gamma$

longitudinal $W^{\pm}$, Z (spin 0)

$+ \ h^0$ (spin 0) yet to be discovered

Standard Model

Fermion and scalar gauge charges:

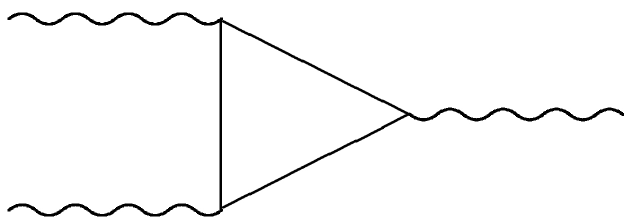
		$SU(3)_C$	$SU(2)_W$	$U(1)_Y$
quark doublet:	$q^i_L = (u^i_L,\, d^i_L)$	3	2	$1/3$
right-handed up-type quark:	u^i_R	3	1	$4/3$
right-handed down-type quark:	d^i_R	3	1	$-2/3$
lepton doublet:	$l^i_L = (\nu^i_L,\, e^i_L)$	1	2	-1
right-handed charged lepton:	e^i_R	1	1	-2
Higgs doublet:	H	1	2	$+1$

$i = 1, 2, 3$ *labels the fermion generations.*

Anomaly cancellation

Gauge symmetries may be broken by quantum effects.

Cure: sums over fermion triangle diagrams must vanish.



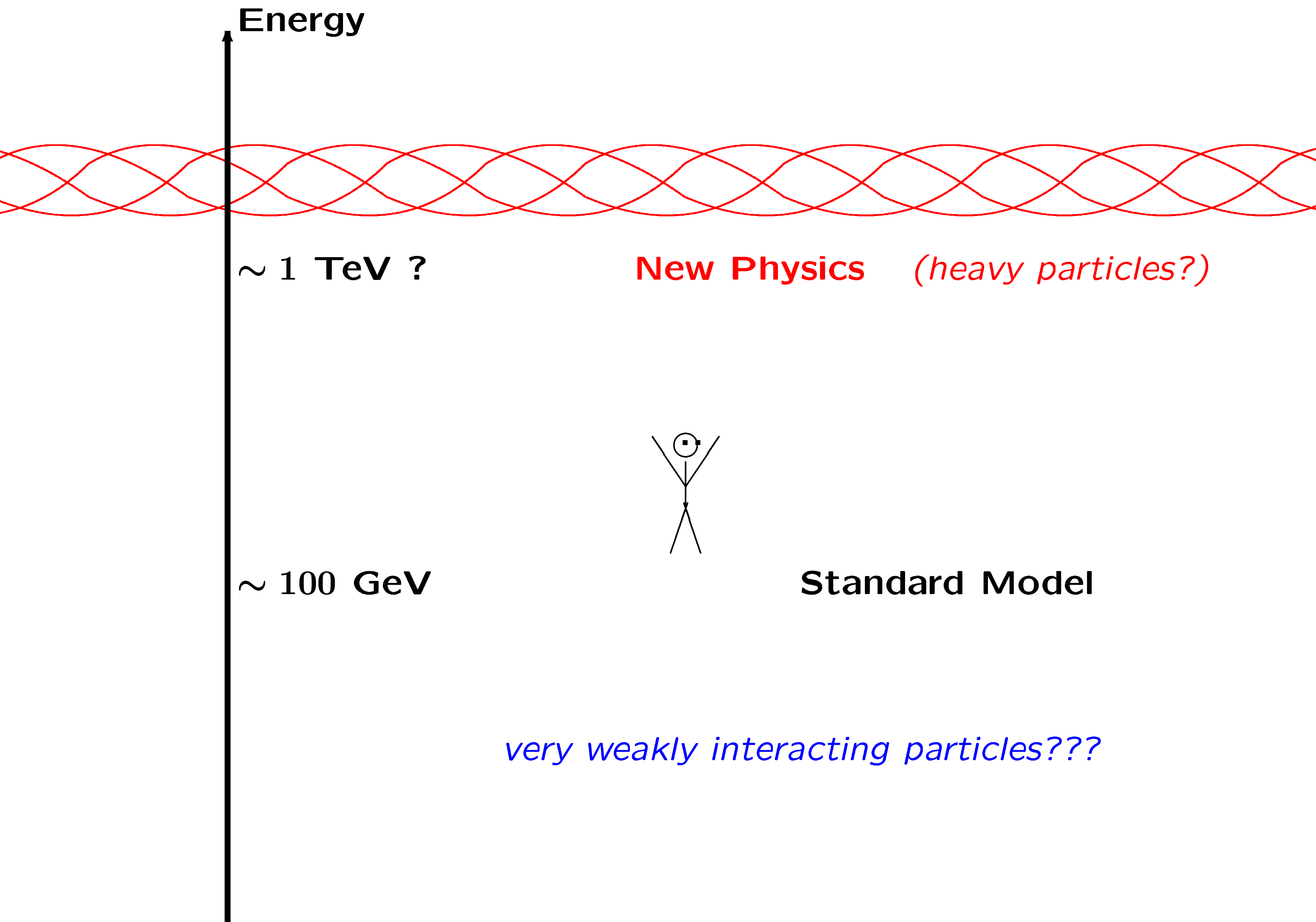
Standard Model: anomalies cancel within each generation

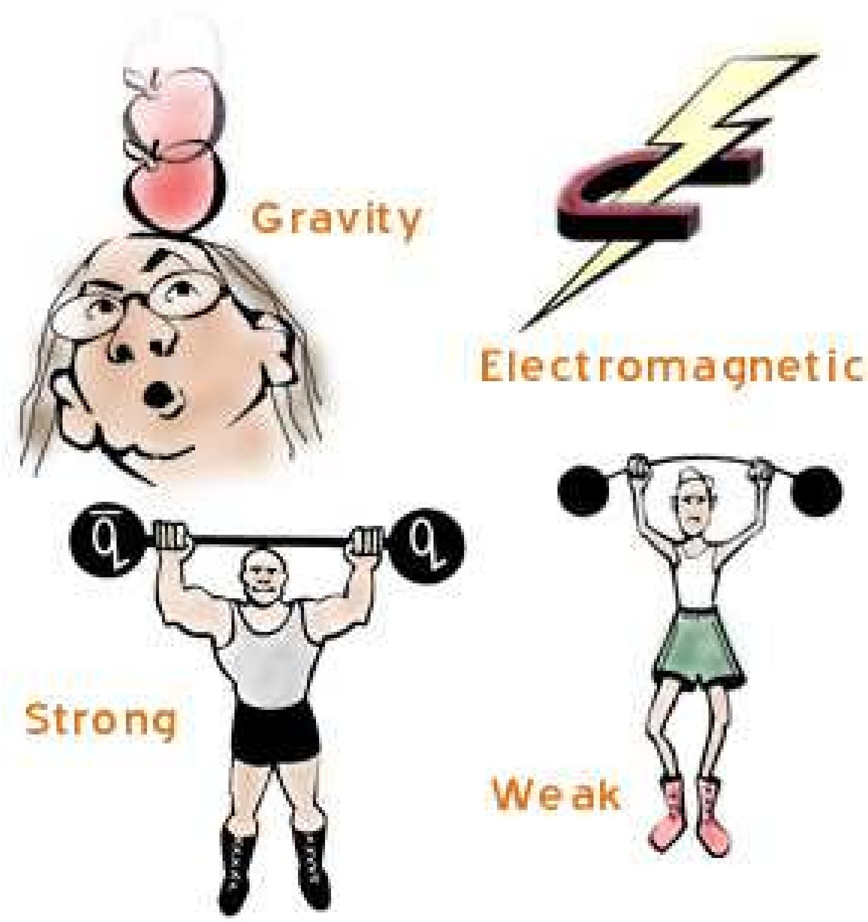
$[SU(3)]^2U(1)$: $\quad 2(1/3) + (-4/3) + (2/3) = 0$

$[SU(2)]^2U(1)$: $\quad 3(1/3) + (-1) = 0$

$[U(1)]^3$: $\quad 3\left[2(1/3)^3 + (-4/3)^3 + (2/3)^3\right] + 2(-1)^3 + (-2)^3 = 0$

$U(1)$-gravitational: $\quad 2(1/3) + (-4/3) + (2/3) = 0$


Energy
~ 1 TeV ?
New Physics
(heavy particles?)
~ 100 GeV
Standard Model
very weakly interacting particles???



$+ \; ?$

Could there exist new gauge bosons?

Yes, if they are sufficiently heavy ...

(new gauge symmetry must be spontaneously broken)

Z' gauge boson

Consider an $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_z$ gauge symmetry spontaneously broken down to $SU(3)_C \times U(1)_{\rm em}$ by the VEVs of a doublet H and an $SU(2)_W$-singlet scalar, φ.

Three electrically-neutral gauge bosons: γ, Z, Z'.

"Nonexotic" Z' (*T. Appelquist, B. Dobrescu, A. Hopper: hep-ph/0212073*)

Assume:

- generation-independent charges,
- quark and lepton masses as in the standard model,
- no new fermions other than an arbitrary number of ν_R's

Fermion and scalar gauge charges:

	$SU(3)_C$	$SU(2)_W$	$U(1)_Y$	$U(1)_z$
q_L^i	**3**	**2**	$1/3$	z_q
u_R^i	**3**	**1**	$4/3$	z_u
d_R^i	**3**	**1**	$-2/3$	$2z_q - z_u$
l_L^i	**1**	**2**	-1	$-3z_q$
e_R^i	**1**	**1**	-2	$-2z_q - z_u$
ν_R^k , $k = 1, ..., n$	**1**	**1**	0	z_k
H	**1**	**2**	$+1$	$-z_q + z_u$
φ	**1**	**1**	0	1

$[SU(3)_C]^2 U(1)_z$, $[SU(2)_W]^2 U(1)_z$, $U(1)_Y [U(1)_z]^2$ and $[U(1)_Y]^2 U(1)_z$ anomalies cancel

Gravitational-$U(1)_z$ and $[U(1)_z]^3$ anomaly cancellation conditions:

$$\frac{1}{3}\sum_{k=1}^{n} z_k = -4z_q + z_u$$

Diophantine equation!

$$\left(\sum_{k=1}^{n} z_k\right)^3 = 9\sum_{k=1}^{n} z_k^3$$

Nontrivial solutions only if the number of ν_R is $n \geq 3$.

(*e.g.* $z_1 = z_2 = z_3 = -4z_q + z_u$)

Special case: $SU(3)_C \times SU(2)_W \times U(1)_Y \times U(1)_{B-L}$

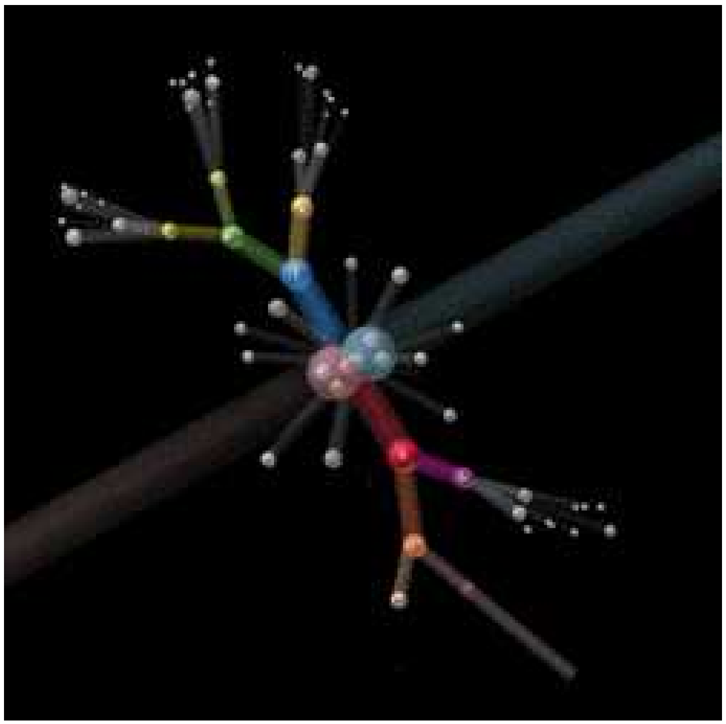
Charges given by the baryon minus lepton number:

$$z_q = z_u = z_d = -\frac{z_l}{3} = -\frac{z_e}{3} = -\frac{z_\nu}{3} \quad , \quad z_H = 0$$

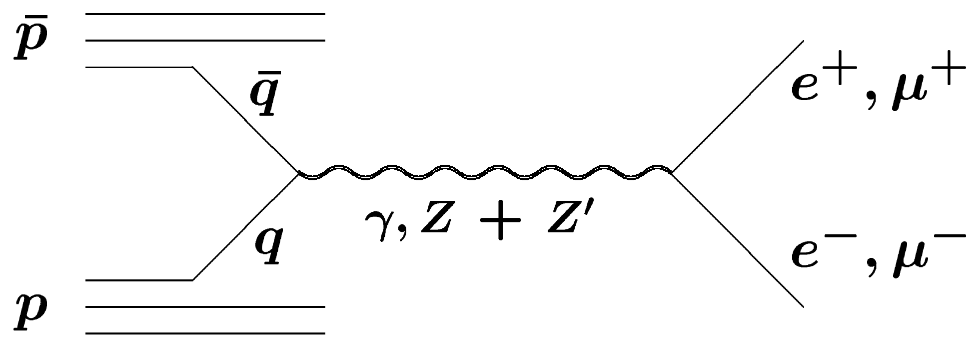
no Z'-Z mixing (tree level) $\Rightarrow$ no constraints from electroweak measurements

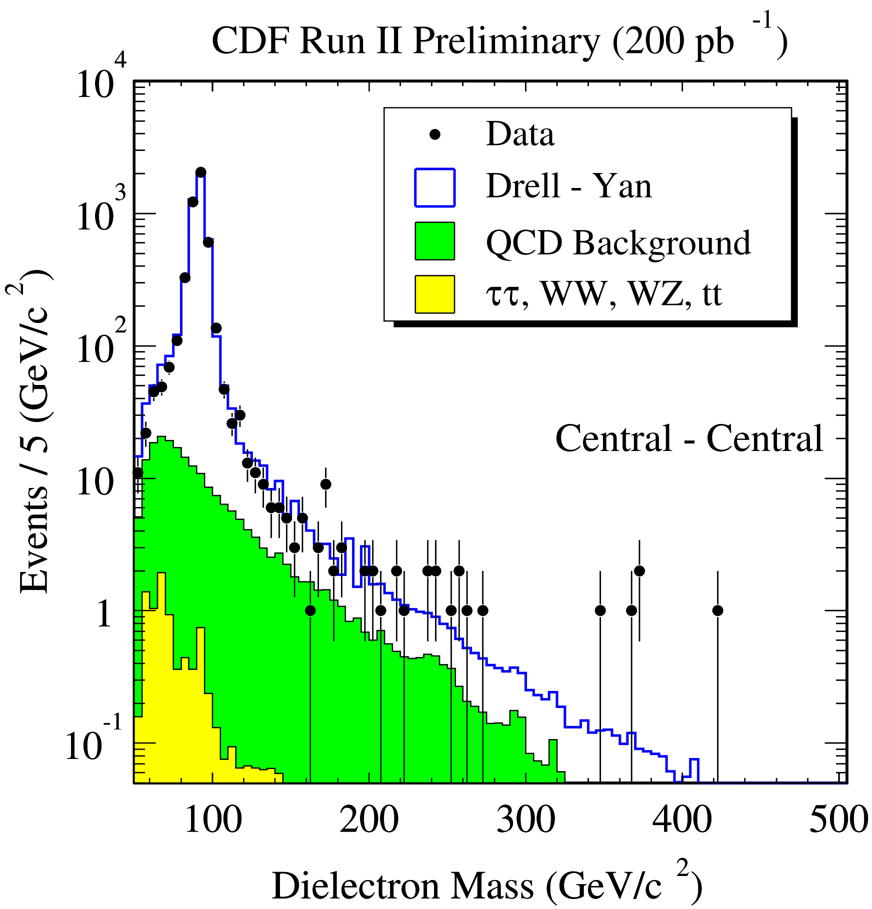
Tevatron collider at Fermilab:

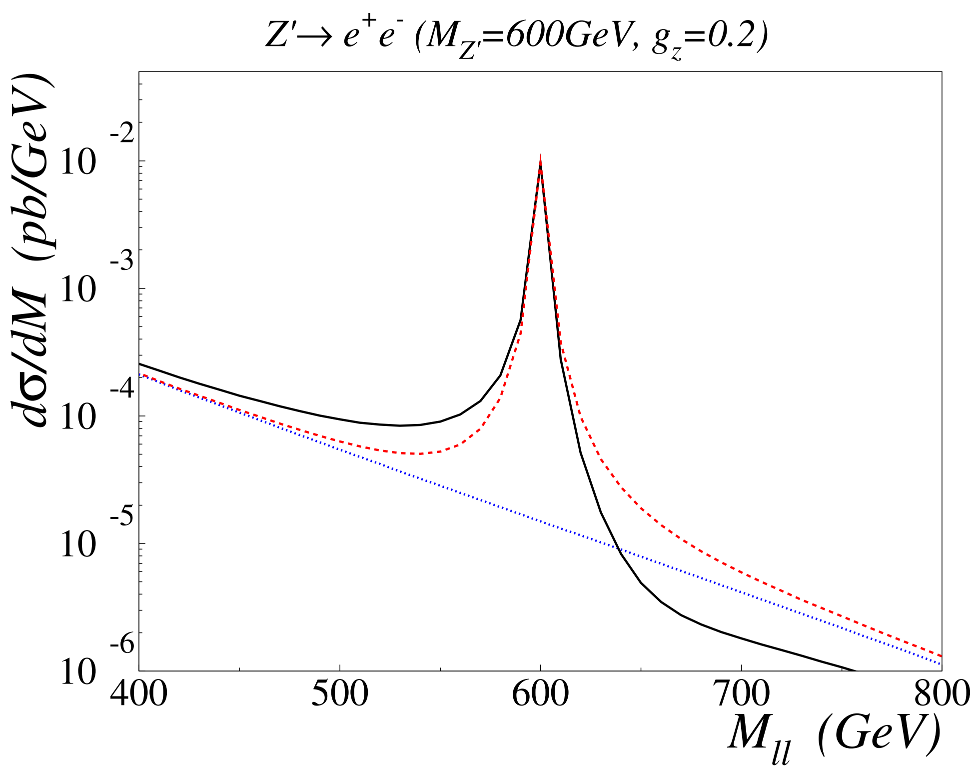
$p\bar{p}$ **collisions at 2 TeV analyzed with the D0 and CDF detectors**



Z' searches at the Tevatron

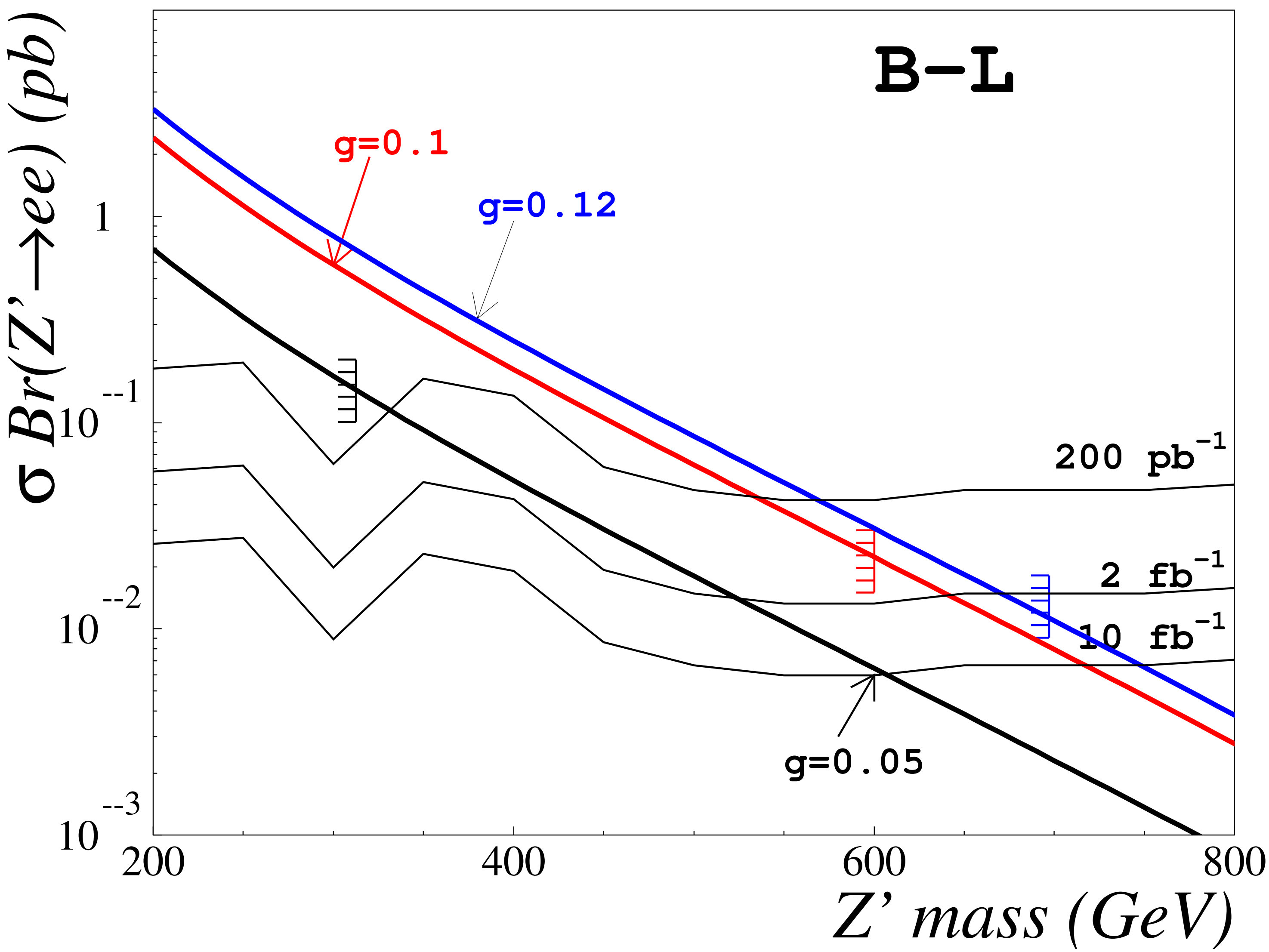






M. Carena, A. Daleo, B. Dobrescu, T. Tait: hep-ph/0408098

Z' searches at the Tevatron:



More general charges are allowed in the presence of new fermions:

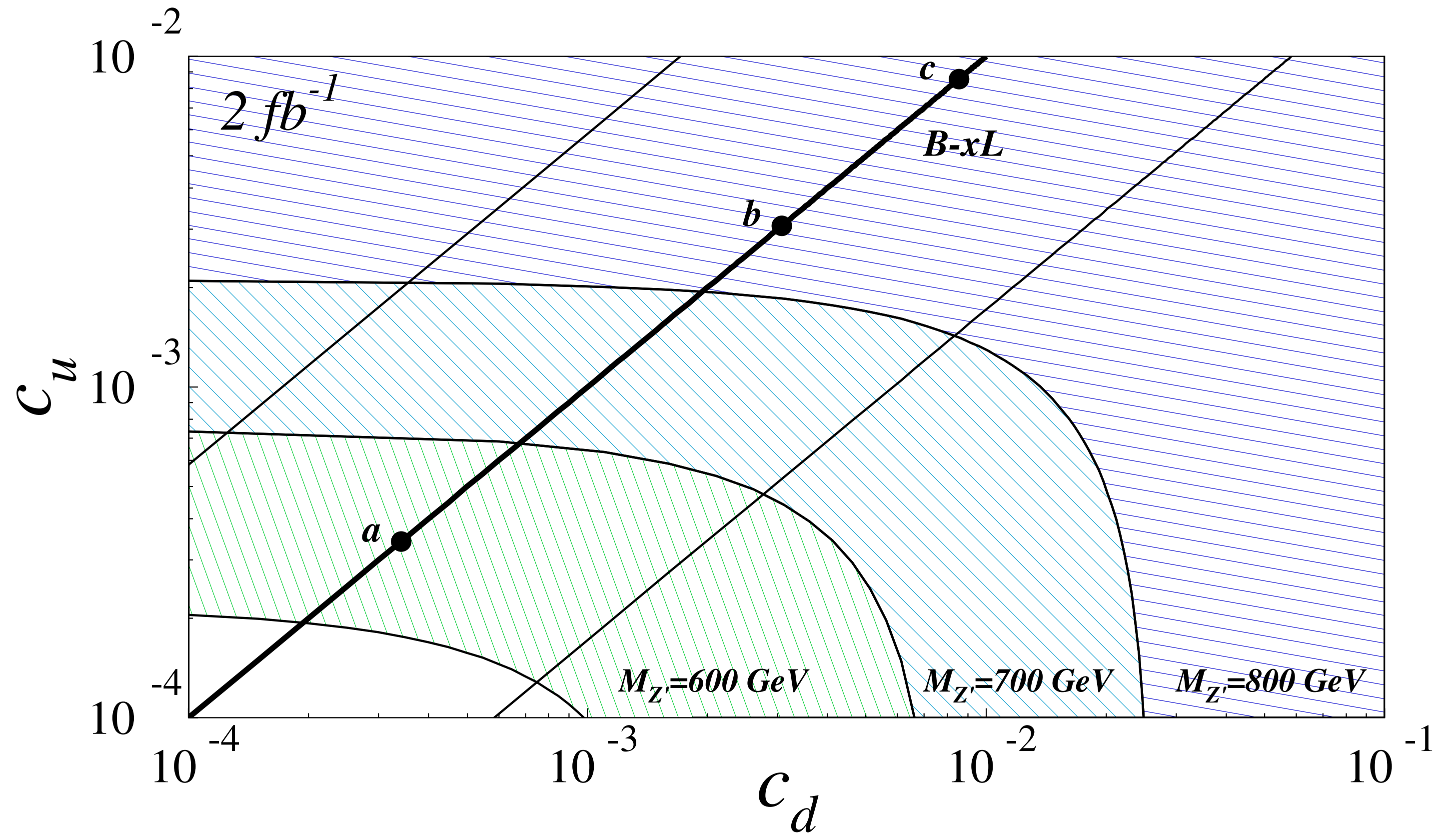
	$SU(3)$	$SU(2)$	$U(1)_Y$	$U(1)_{B-xL}$	$U(1)_{q+xu}$	$U(1)_{10+x\bar{5}}$	$U(1)_{d-xu}$
q_L	3	2	$1/3$	$1/3$	$1/3$	$1/3$	0
u_R	3	1	$4/3$	$1/3$	$x/3$	$-1/3$	$-x/3$
d_R	3	1	$-2/3$	$1/3$	$(2-x)/3$	$-x/3$	$1/3$
l_L	1	2	-1	$-x$	-1	$x/3$	$(-1+x)/3$
e_R	1	1	-2	$-x$	$-(2+x)/3$	$-1/3$	$x/3$
ν_R	1	1	0	-1	$(-4+x)/3$	$(-2+x)/3$	$-x/3$
ν'_R				$\cdot$	$\cdot$	$-1-x/3$	$\cdot$
ψ^l_L	1	2	-1	-1	$\cdot$	$-(1+x)/3$	$-2x/5$
ψ^l_R				$-x$	$\cdot$	$2/3$	$(-1+x/5)/3$
ψ^e_L	1	1	-2	-1	$\cdot$	$\cdot$	$\cdot$
ψ^e_R				$-x$	$\cdot$	$\cdot$	$\cdot$
ψ^d_L	3	1	$-2/3$	$\cdot$	$\cdot$	$-2/3$	$(1-4x/5)/3$
ψ^d_R				$\cdot$	$\cdot$	$(1+x)/3$	$x/15$

A user-friendly parametrization:

$$\sigma\left(p\bar{p}\to Z'X\to l^+l^-X\right)=\frac{\pi}{48\,s}\left[c_u\,w_u\left(\frac{M_{Z'}^2}{s},M_{Z'}\right)+c_d\,w_d\left(\frac{M_{Z'}^2}{s},M_{Z'}\right)\right]$$

All the information about charges is contained in:

$$c_{u,d}=g_z^2\,(z_q^2+z_{u,d}^2)\,\text{Br}(Z'\to l^+l^-)$$



LHC collider: proton-proton collisions at 14 TeV analyzed with the ATLAS and CMS detectors

(will start getting data in 2008)

$$\sigma\left(pp \to Z'X \to l^+l^-X\right) = \frac{\pi}{48\,s}\left[c_u\,w'_u\left(\frac{M_{Z'}^2}{s}, M_{Z'}\right) + c_d\,w'_d\left(\frac{M_{Z'}^2}{s}, M_{Z'}\right)\right]$$

w'_u and w'_d contain all the information about QCD:

values at the LHC are different than at the Tevatron

$\Rightarrow$ c_u and c_d can be determined independently if a Z' is observed at both the Tevatron and the LHC.

More information about Z' couplings ($U(1)_z$ charges) can be extracted from angular distributions, etc.

∼ 530 B.C. Pythagoras theorizes that the Earth is round
(to explain the circular shadow during lunar eclipses)

∼ 250 B.C. Erathostenes measures indirectly the Earth size
(∼ 39 000 km, with large systematical errors)

140 A.D. Ptolemy draws the World Map using an Earth
size smaller by 30%.

1482 A.D. World Map (by Donnus Nicolaus Germanus):

1492 A.D.

C. Columbus performs an experimental test,

and concludes that the theory is correct.

But he was wrong: he discovered something else ...

Here's the detector used ("La Nina", $15\ m$ long):

Could there exist massless gauge bosons other than the photon?

$U(1)_{B-L}$ is the only global symmetry of the standard model that can be gauged and unbroken.

Z_{B-L} coupling to ordinary matter: $N_n \, g_z$
($N_n =$ number of neutrons)

To avoid deviations from Newton's law:

$$g_z \ll \frac{m_n}{M_{\rm Pl}} \sim 10^{-19}$$

Tests of the equivalence principle: $g_z < 10^{-24}$

But **even when** $z_q = z_u = z_d = z_l = z_e = 0$

there can still be interactions of the standard model fields with the new massless gauge boson:

higher-dimensional operators!

(interactions with strength suppressed by some mass scale)

B.D., hep-ph/0411004

γ' **couplings to leptons:**

$$\frac{C_e}{M^2} P_{\mu\nu} \left(\bar{l}_L \sigma^{\mu\nu} e_R H + \mathrm{h.c.}\right)$$

$P_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ **(γ' field strength)**

C_e**: dimensionless parameters**

(3×3 *matrix in flavor space*)

γ' **couplings to quarks: similar dimension-6 operators**

In the mass eigenstate basis $C_e \to C'_e = U^e_L C_e U^{e\dagger}_R$

U^e_L and U^e_R are the unitary matrices that diagonalize the masses of the electrically-charged leptons.

• Interactions of the mass-eigenstate leptons with P^μ (chirality-flip operators $\sim v_h \approx 174$ GeV) :

$$\frac{v_h}{M^2} P_{\mu\nu}\, \overline{e'} \sigma^{\mu\nu} \left(\mathrm{Re} C'_e + i\, \mathrm{Im} C'_e\, \gamma_5\right) e'$$

$\to$ magnetic-like and electric-like dipole moments

$\mathrm{Re}(C'_e)^{ij}$, $\mathrm{Im}(C'_e)^{ij}$ could have any value $\lesssim 4\pi$, but:

chirality-flip operators $\Rightarrow$ $\quad \left|C'^{11}_e\right| \lesssim \dfrac{m_e}{v_h} \approx 3 \times 10^{-6}$

The strength of the γ' interaction with the electrons depends on

$$c_e \equiv \frac{v_h}{m_e} \left|\left(C'_e\right)_{11}\right| \lesssim O(1)$$

Similar parameters defined for interactions
such as $\mu^+\mu^-\gamma'$, $\mu^\pm e^\mp \gamma'$, ...

Various measurements set limits on these parameters.

Kinetic mixing of $U(1)_Y \times U(1)_z$ gauge bosons:

$c_0 B^{\mu\nu} P_{\mu\nu}$ dimension-four operator!

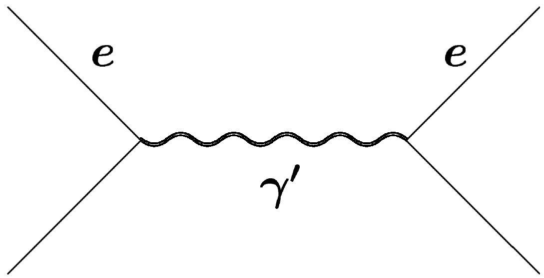
Holdom 1985:

Kinetic terms can be diagonalized and canonically normalized by a $SL(2,R)$ transformation.

Global $SO(2)$ symmetry: linear combination of $U(1)$ fields that couples to hypercharge is the real B^μ.

Orthogonal combination ("paraphoton" $= \gamma'$) does not have any renormalizable couplings to standard model fields.

Conclusion:
kinetic mixing has no effect on the standard model fields other than a renormalization of the hypercharge gauge coupling.



In the nonrelativistic limit: long-range forces induced by γ' are spin-dependent *(work with Irina Mocioiu)*

$$V(\vec{r}) = -\frac{c_e^2 m_e^2}{\pi M^4}\,\frac{1}{r^3}\left[\frac{3}{r^2}(\vec{\sigma_1}\cdot\vec{r})(\vec{\sigma_2}\cdot\vec{r}) - \vec{\sigma_1}\cdot\vec{\sigma_2}\right]$$

Measurements of $e-e$ long range forces impose that

$$\frac{M}{\sqrt{c_e}} \gtrsim 3\ \mathrm{GeV}$$

Flavor-changing neutral currents

Chirality-flip transition:

$$\Gamma\left(\mu \to e\gamma'\right) = c_{e\mu}^2 \frac{m_\mu^5}{8\pi M^4}$$

Standard model:

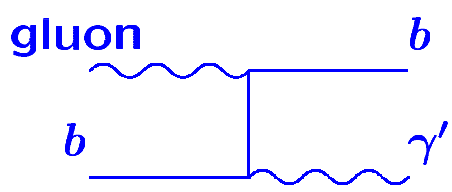
$$\Gamma\left(\mu \to e\nu\bar{\nu}\right) = \frac{m_\mu^5 G_F^2}{192\pi^3} \approx 3.2 \times 10^{-10}\mathrm{eV}$$

$$\mathrm{Br}\left(\mu \to e\gamma'\right) < 3 \times 10^{-5} \qquad \Rightarrow \qquad \frac{M}{\sqrt{c_{e\mu}}} \gtrsim 15\ \mathrm{TeV}$$

LHC - “factory” of heavy particles, but also:

γ' production at the LHC

Example: monojet + missing energy



LHC - “factory” of massless particles!

LHC will also probe the physics that generate the higher-dimensional operators at the scale M.

Primordial Nucleosynthesis

Constraints on new particles with mass below several MeV.

Maximum number of new relativistic degrees of freedom:

$$\Delta g_*^{\max} = \frac{7}{8}\Delta N^{\max} \; ; \quad \text{at the } 2\sigma \text{ level:} \quad \Delta N_\nu^{\max} \approx 0.6$$

γ' must go out of equilibrium at $T_P > T_{\rm BBN} \approx 1$ MeV

Number of degrees of freedom contributed by γ' during BBN:

$$\Delta g_*(T_{\rm BBN}) = 2\left[\frac{g_*(T_{\rm BBN})}{g_*(T_P)}\right]^{4/3} \quad \longrightarrow \quad g_*(T_P) > \frac{20.0}{(\Delta N_\nu^{\rm max})^{3/4}} \gtrsim 30$$

Freeze-out temperature:

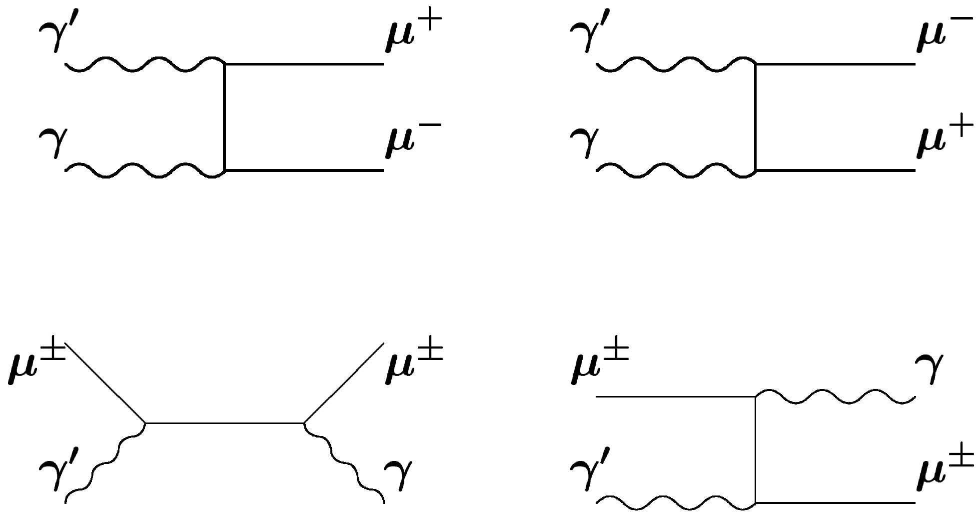
$$T_P > T_{\rm QCD} \approx 150 - 180 \text{ MeV}$$

$$g_*(T_P) = 247/4$$

(for $T_P \lesssim T_{\rm QCD}$*:* $g_* = 69/4$ *is too small)*

At $T \approx 200$ MeV: $\gamma', \gamma, e, \mu, u, d, g, \nu_e, \nu_\mu, \nu_\tau$ are in equilibrium.

Dominant γ' annihilation channels:



Interaction rate of γ': $\Gamma = n_{\gamma'} \langle \sigma |v| \rangle$

Number density of γ': $n_{\gamma'} = \frac{2\zeta(3)}{\pi^2} T^3 \approx 0.24\, T^3$

Thermally averaged cross section: $\langle \sigma |v| \rangle \sim \frac{\alpha c_\mu^2 m_\mu^2}{M^4}$

Expansion rate of the universe: $$H \approx \frac{T^2}{M_{\rm Pl}} \left(\frac{2\pi^3}{45} g_*(T) \right)^{1/2}$$

At the freeze-out temperature: $\Gamma_s \approx H$

$$\Longrightarrow \quad \frac{M}{\sqrt{c_\mu}} \approx 3.9 \text{ TeV} \times [g_*(T_P)]^{-1/8} \left(\frac{T_P}{1 \text{ GeV}} \right)^{1/4}$$

Measurements of light element abundances set a limit on the effective mass scale:

$$M \gtrsim 1.5 \text{ TeV} \times \sqrt{c_\mu}$$

Star cooling

Effective coupling of γ' to electrons: $$g_{\gamma' e} = \frac{c_e}{M^2} m_e^2$$

Red giant stars: γ' emission via Bremsstrahlung & Compton-like processes

$$g_{\gamma' e}^2 / 4\pi < 2.5 \times 10^{-27} \quad \Rightarrow \quad \frac{M}{\sqrt{c_e}} \gtrsim 3.2 \text{ TeV}$$

For supernovae: ν emission rate $\gg$ γ' emission rate
$\Rightarrow$ no useful bound on electron-γ' coupling
(strong bound on quark-γ' couplings)

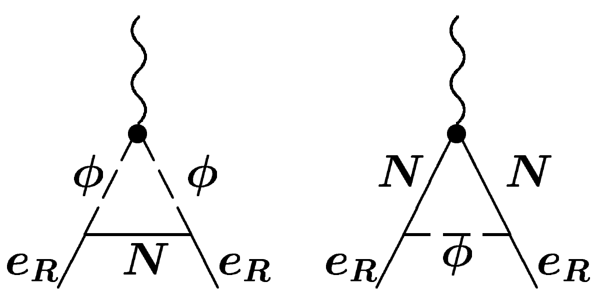
Lower limits on the mass scales that supress various operators:

Mass scale	Limit (TeV)	Process
$M/\sqrt{c_e}$	0.003	$e-e$ spin-dependent forces
	3.2	Bremstrahlung in red giants
	1.8	Compton scattering in stars
$M/\sqrt{c_n}$	7	SN1987A cooling
	0.4	BBN
$M/\sqrt{c_{e\mu}}$	15	$\mu \to e\gamma'$
$M/\sqrt{c_\mu}$	1.5	BBN
$M/\sqrt{c_s}$	1.8	BBN
$M/\sqrt{c_0 c_\mu}$	12	$g_\mu - 2$

	l_L	e_R	N_L	N_R	H	ϕ
$SU(2)_W$	2	1	1	1	2	1
$U(1)_Y$	-1	-2	0	0	$+1$	-2
$U(1)_p$	0	0	$+1$	$+1$	0	-1

Yukawa interaction: $\lambda_\phi^j \, \overline{e}_R^j N_L \, \phi + \mathrm{h.c.}$

Contribution to the $iP_{\mu\nu}\overline{e}_R\gamma^\mu\partial^\nu e_R$ operator ($\sim P_{\mu\nu}\bar{l}_L\sigma^{\mu\nu}e_R H$):



$$\Rightarrow \quad (C_e)_{ij} = \frac{g_p}{192\pi^2}\sum_k \left(\lambda_\phi^i \lambda_\phi^{*k} \lambda_e^{kj} + \lambda_e^{ik} \lambda_\phi^k \lambda_\phi^{*j}\right)$$

Conclusions

New massless gauge boson may couple to quarks and leptons via dimension-6 operators suppressed by a scale $\lesssim$ 1 TeV!

The lightest particle charged under the new $U(1)$ is a dark matter candidate.

At the LHC: look not only for heavy particles (Z', ...), but also for massless ones (γ') coupling to t or b quarks.